HY-2A Radar Altimeter Ultra Stable Oscillator Drift Estimation Using Reconstructive Transponder with Its Validation by Multi-mission Cross-Calibration (Postprint)

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Abstract

The paper presents a method for estimating the Ultra Stable Oscillator (USO) drift of the HY-2A altimeter using a reconstructive transponder. The frequency of the USO aboard the in-orbit altimeter varies with age, resulting in a bias between the actual frequency and the nominal frequency. This USO bias contributes to a portion of the altimeter' s range drift. During calibration, the HY-2A altimeter transmits signals at a fixed time interval; however, due to USO drift, the actual interval between adjacent altimeter transmissions, which is controlled by the USO, differs from the nominal interval. The reconstructive transponder accurately measures the arrival times of the altimeter's transmitted signals using an atomic clock. The drift of the USO onboard the HY-2A altimeter can be accurately estimated by utilizing range measurements from both the reconstructive transponder and the HY-2A altimeter. USO drifts of approximately 40 cm/year are reported. Furthermore, multi-mission cross-calibration provides preliminary validation of the HY-2A altimeter' s USO drift.

Full Text

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Abstract—This paper presents a method for estimating the HY-2A altimeter ultra stable oscillator (USO) drift using a reconstructive transponder. The frequency of the USO in an in-orbit altimeter changes with age, creating a bias between the actual and nominal frequencies. This USO bias contributes to the altimeter range drift. During calibration, the HY-2A altimeter transmits signals at fixed time intervals, but the actual interval between adjacent altimeter transmissions—controlled by the USO—differs from the nominal value due to USO drift. The reconstructive transponder measures the arrival times of altimeter-transmitted signals accurately using an atomic clock. The drift of the USO onboard the HY-2A altimeter can be estimated precisely by comparing ranges from the reconstructive transponder and the HY-2A altimeter. The results show USO drifts of approximately 40 cm/year. Furthermore, multi-mission cross-calibration provides preliminary validation of the HY-2A altimeter USO drift.

Index Terms—Calibration, radar altimetry, transponders, oscillators, frequency.

I. INTRODUCTION

The essence of radar altimeter range measurement is the two-way travel time measurement of an altimeter-transmitted pulse, with travel time calculated by counting clock cycles generated by an onboard ultra stable oscillator (USO). The oscillator frequency changes slowly with age, and USO drift contributes to radar altimeter range bias. The range bias ΔH introduced by USO drift can be written as $\Delta H = H \times \Delta f$, where H is the altimeter altitude above the Earth' s surface, Δf is the USO frequency bias, and f_0 is the reference oscillator frequency.

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Several advanced approaches exist for calibrating altimeter USO drift. **Approach I**: Lillibridge et al. [**?**] reprocessed Waveform Data Records (WDRs) and Sensor Data Records (SDRs) from the Geodetic Mission (GM) of Geosat to obtain an oscillator drift model using time items from SDRs and WDRs. This model claims to achieve range-dilation correction at the 1 mm level. However, we believe drift calibration through data record reprocessing is difficult to implement for operational altimetry services. For example, the Jason-1 mission provides Interim Geophysical Data Records (IGDR) with a 3-day latency [?], and the OSTM/Jason-2 mission provides IGDR with a 1-day latency [?]. **Approach II**: Scharroo et al. [?] proposed a method to model and correct the ENVISAT RA-2 altimeter range bias attributed to anomalous USO operation by using both the Instrument Control Unit (ICU) clock and the USO that provides the frequency standard for the altimeter. **Approach III**: For ERS-1/2, the USO frequency is measured once per week over a specific ground station. The USO frequency is recovered on the ground and compared with an atomic frequency standard to obtain the USO drift correction [?]. **Approach IV**: DORIS (Doppler Orbitography and Radio positioning Integrated in Space) instruments onboard Jason-1, OSTM/Jason-2, and SARAL/AltiKa altimetry satellites provide 10 MHz frequency references for the Poseidon-2/3 and SARAL/AltiKa altimeters [?], [?], and the actual USO frequency can be derived from DORIS data [?]. The Poseidon altimeter onboard TOPEX/Poseidon also uses time reference provided by DORIS [?]. **Approach V**: The Time Transfer by Laser Link (T2L2) experimental system onboard Jason-2 provides a novel approach for monitoring DORIS oscillator drift [?], [?]. In our opinion, approaches III, IV, and V are preferable for USO calibration as they rely on space-ground time transfer. These approaches depend on a stable USO onboard the altimeter and accurate monitoring of USO evolution performed on the ground.

MacDoran et al. [?] proposed an active transponder for TOPEX/Poseidon satellite altimetry calibration in 1991, later called an Active Transponder for Altimetry Calibration (ATAC). Mathews [?] reported the design, laboratory tests, and ground field tests of the ATAC. Compared with traditional transponders for radar altimeter calibration that receive and retransmit amplified original pulses, the ATAC reconstructs a pulse and sends it back. This signal reconstruction feature enables the ATAC to adjust the response pulse delay precisely. In the following sections, we refer to this ATAC-type transponder as a reconstructive transponder unless otherwise stated.

China's marine dynamic environment satellite HY-2A was successfully launched on August 16, 2011, with a nominal orbit altitude of 971 km. A dual-frequency (Ku and C band) radar altimeter is one of HY-2A' s main payloads [?], [?]. The HY-2A altimeter is a fully redundant system providing two parallel independent instruments that share a common antenna to meet instrument life requirements, with each instrument (side A and side B) having its own independent USO. For this purpose, our laboratory—the Key Laboratory of Microwave and Remote Sensing Technology (Mirslab), CAS (Chinese Academy of Sciences)—developed a reconstructive transponder for calibrating active payloads on HY-2A [?], [?]. Since August 2012, the reconstructive transponder has been used in the HY-2A altimeter calibration campaign. Discrepancies between ground and altimeter observations were observed and attributed to USO drift onboard the HY-2A altimeter (the nominal frequency of the HY-2A altimeter USO is 80 MHz).

The USO drift corrections presented in this paper are preliminary. The reconstructive transponder utilizes an atomic rubidium clock to generate an accurate time reference. The calibration process consists of four steps: (1) the altimeter transmits a signal; (2) the reconstructive transponder receives the signal; (3) the reconstructive transponder transmits a reconstructed response signal; and (4) the altimeter receives the response signal. This process can also be considered a time transfer process during which the altimeter USO drift is estimated using altimeter and reconstructive transponder observations. Estimating USO drift onboard radar altimeters using reconstructive transponders has not been previously reported in the literature. In this context, the reconstructive transponder plays a key role in estimating HY-2A altimeter USO drift.

During the calibration campaign, a HY-2A altimeter range bias drift of 40 cm/year was observed, considered to be caused by USO drift. Bosch et al. provided evidence of HY-2A drift through multi-mission cross-calibration [?]. As rigorously calibrated radar altimetry systems, Jason-1 and OSTM/Jason-2 missions with no mean sea level (MSL) drift are sufficient for preliminary validation of HY-2A range drift [?]. Therefore, crossover differences between HY-2A altimeter MSL observations and Jason-1 and OSTM/Jason-2 MSL observations are utilized to verify HY-2A altimeter range bias introduced by USO drift.

Details of the reconstructive transponder approach are elaborated in the remaining sections. Section II presents formulas for ranges from both the altimeter and reconstructive transponder and explains the approach for simplifying biases introduced by the atmosphere. Section III provides the principle of USO drift estimation. Section IV shows HY-2A USO drift estimation results and corresponding verifications from multi-mission cross-calibration. Section V summarizes concluding remarks.

II. ALTIMETER AND TRANSPONDER OBSERVED RANGES

[Figure 1: see original paper] shows the geometric relationship between the altimeter and the reconstructive transponder. The HY-2A altimeter switches to search mode before overflying the reconstructive transponder. In this mode, the altimeter transmits signals at interval t_{att}, while t_{atr} is the interval between transmission and corresponding reception, and these two intervals are preset constants.

Tropospheric delays, ionospheric delays, and instrumental delays exist in ranges observed by both the altimeter and reconstructive transponder. The instrumental delay of the reconstructive transponder can be taken as a constant D_{tra}, and the instrumental delay of the altimeter introduced by the internal signal path can be taken as a constant D_{alt} (long-term altimeter/transponder path delay changes will not affect the final USO frequency estimation, as discussed following equation (10)). The zenith path delay introduced by the troposphere and ionosphere can be taken as constants D_{tro} and D_{ion}; a detailed derivation is contained in the appendix. Ground-based global positioning system

(GPS) equipment is used to obtain tropospheric delay, and total electron content (TEC) global maps from the International GNSS Service (IGS) are used to obtain ionospheric delay. However, the values of D_{tro} and D_{ion} are not used for USO frequency estimation (they are used in further calibration data processing).

Let $R(t)$ be the distance between the altimeter and reconstructive transponder, expressed as $R(t) = at^2 + bt + c; a \neq 0$, where a, b, and c are constants [?]. During calibration, Doppler effect introduces bias in altimeter and reconstructive transponder observations. Let $R_k; k = 0, 2, ...$ be the ranges between altimeter and reconstructive transponder when the altimeter transmits signals, and $R_k; k = 1, 3, ...$ be the ranges when the altimeter receives response signals. As an example, [Figure 1: see original paper] shows four ranges, R_0 to R_3. Based on the above discussion of biases in observed ranges, letting the sum of D_{tra} and D_{alt} be D_{ins}, and the sum of D_{tro} and D_{ion} be D_{atm}, and considering the Doppler effect, we obtain $D_t(k)$, the kth range observed by the reconstructive transponder:

$$\begin{aligned} D_t(k) &= (Ct_{att} + R_{2k} + D_{ins} + D_{atm}) - (R_{2(k-1)} + D_{ins} + D_{atm}) + Dop_{tr} \quad (2) \\ &= Ct_{att} + R_{2k} - R_{2(k-1)} + \frac{2at_{att}}{\lambda} \end{aligned}$$

where Dop_{tr} is the Doppler bias, $\lambda = 2.2$ cm is the Ku-band wavelength of the HY-2A altimeter, C is the speed of light in vacuum, and $K = 9.6 \times 10^{-5}$.

$R_a(k)$, the kth range observed by the altimeter, is:

$$R_a(k) = R_{2(k-1)} + R_{2k-1} + D_{ins} + 2D_{atm} + Dop_{alt} \tag{4}$$

where Dop_{alt} is the Doppler bias in $R_a(t)$ and $k = 1, 2, ...$

III. ESTIMATION OF RANGE BIAS DUE TO USO DRIFT

Both the altimeter and reconstructive transponder operate on the full deramp principle; therefore, observed ranges R_{ob} consist of two parts: (1) time-domain range obtained from counting pulses provided by time references (USO onboard the HY-2A altimeter and atomic clock onboard the reconstructive transponder), and (2) frequency-domain range obtained from deramp processing.

The total length of the HY-2A altimeter range window is 60 meters. A 128-point FFT processing divides the window into 128 range cells, giving a frequency-domain one-way range resolution $res_f = 60/128 = 0.46$ m. The frequency-domain range bias from USO drift is:

$$RB_{freq} = \frac{F_{B\_USO}}{80\text{MHz}} \times res_f \tag{5}$$

where RB_{freq} is the frequency-domain range bias from USO drift and F_{B_USO} is the frequency bias of the HY-2A altimeter USO. Since F_{B_USO} is no more than 100 Hz, RB_{freq} is no more than 6×10^{-7} m. Therefore, RB_{freq} is negligible.

[Figure 2: see original paper] shows the altimeter timing diagram with and without USO drift. T_{a0} is the nominal 12.5 nanosecond period of the time references for the HY-2A altimeter and reconstructive transponder, and ΔT_a is the clock period bias. t_{att} and t_{atr} are predetermined integer multiples of T_{a0}. The multiples N_{at} and N_{ar} are determined by:

$$N_{at} = N_{ar} = \frac{t_{att}}{T_{a0}}$$

The pulse in [Figure 2: see original paper] represents the timing pulse from the altimeter' s clock. The altimeter transmits signal Sg_0 at E_1, the rising edge of the 1st pulse. The echo signal corresponding to Sg_0 is received at E_3, the rising edge of the $(N_{ar}+1)$th pulse. At E_2, the rising edge of the $(N_{at}+1)$th pulse, the altimeter transmits signal Sg_1. The time interval between E_1 and E_2 is t_{att}, and the interval between E_1 and E_3 is t_{atr}.

N_{at} is uploaded to the HY-2A altimeter before calibration. Considering the existence of ΔT_a and using (6), the Ct_{att} term in (3) becomes $CN_{at}(T_{a0}+\Delta T_a)$. Subtracting Ct_{att} from (3), we obtain:

$$\begin{aligned}\hat{D}(t) &= CN_{at}\Delta T_a + R_{2k} - R_{2(k-1)} + Dop_{tr} \\ &= CN_{at}\Delta T_a + t_{att}(2at' + b) + \frac{2at_{att}}{\lambda}\end{aligned} \tag{7}$$

where $t' = t + \frac{t_{atr}}{2}$. According to [Figure 1: see original paper], $R_{2(k-1)}$ and R_{2k} are adjacent ranges observed by the reconstructive transponder, and $R_{2k} - R_{2(k-1)}$ is an adjacent range difference. Therefore, $\hat{D}(t)$ can be taken as the sum of an adjacent range difference term, a USO range bias term $CN_{at}\Delta T_a$, and a Doppler bias term.

Using (4) and (2), $R_a(t)$, the range observed by the altimeter, can be expressed as:

$$\begin{aligned}R_a(t) &= at^2 + bt + c + a(t+t_{atr})^2 + b(t+t_{atr}) + c + Dop_{alt} \\ &= 2a(t')^2 + (2b + 4a\frac{t_{att}}{\lambda})(t') + CN_{at}\Delta T_a + C_1\end{aligned} \tag{8}$$

where C_1 is a constant. $\hat{D}(t)$ and $R_a(t)$ are respectively linear and quadratic functions of t'. Therefore, $CN_{at}\Delta T_a$, the range bias introduced by HY-2A altimeter USO frequency drift, can be written as:

$$CN_{at}\Delta T_a = \hat{b} - \frac{t_{att}}{2} b' \quad (9)$$

where $\hat{b}$ is the constant coefficient of $\hat{D}(t)$ and b' is the linear coefficient of $R_a(t)$, both obtained by least squares method. The Doppler effects in $\hat{D}(t)$ and $R_a(t)$ are eliminated, and D_{ins} and D_{atm}, which are contained in C_1 in (8), do not affect the estimation of ΔT_a.

Δf is the frequency bias of the 80 MHz clock controlling HY-2A altimeter operations, expressed as:

$$\Delta f = \frac{\Delta T_a}{T_{a0}(T_{a0} + \Delta T_a)} \quad (10)$$

where $f_0 = 1/T_{a0}$ is the nominal USO frequency. Before using (9), correspondence must be established between ranges observed by the altimeter and reconstructive transponder, using a matching method introduced in [**?**].

[Figure 3: see original paper] shows ranges observed by the HY-2A altimeter and corresponding ranges observed by the reconstructive transponder, obtained on September 2, 2012 in Beijing, China. The major portion of HY-2A altimeter ranges are on the ascending part of the range parabola; therefore, most reconstructive transponder ranges should be positive. However, all ranges from the reconstructive transponder are negative due to the bias term $CN_{at}\Delta T_a$ introduced by HY-2A altimeter USO drift. Level 0 search mode data from the HY-2A altimeter and reconstructive transponder data are used for USO drift estimation. The reconstructive transponder’ s ranges are produced during calibration, and as soon as the level 0 search mode data containing the responding ranges are produced, the range bias introduced by the HY-2A altimeter USO can be estimated and used for range bias correction of higher-level data products.

IV. RESULTS, VERIFICATIONS AND DISCUSSIONS

A. HY-2A Altimeter USO Drift Measured by Reconstructive Transponder

All examples below are from processing results of Ku-band data from the HY-2A altimeter and reconstructive transponder, with parameter precisions given as 95% confidence bounds unless stated otherwise. HY-2A USO drift and corresponding range bias observed with the reconstructive transponder are contained in [TABLE:I]. An anomalous behavior of HY-2A altimeter side A’ s USO was reported on March 31, 2013, and side B with an independent USO was brought online on April 2, 2013. From August 9, 2012 to March 2, 2014, a total of 16 USO drift measurements were obtained from HY-2A in situ calibrations using the reconstructive transponder, presented in [Figure 4: see original paper], with corresponding range biases also shown.

A piecewise linear character exists in the range bias introduced by the USO of side A (except for the sample obtained on March 31, 2013, the same day the anomalous behavior of side A' s USO was reported), while a single linear trend exists in side B samples. The slope of each piece is presented. The range bias introduced by the USO can be modeled as:

$$\text{range bias} = \begin{cases} 5.36 \times 10^{-4} d + 0.164; & \text{side A} : d \in [359, 467] \\ 3.10 \times 10^{-5} d + 0.394; & \text{side A} : d \in [467, 579] \\ 1.34 \times 10^{-3} d - 0.697; & \text{side B} : d \in [635, 929] \end{cases}$$

where d is the number of days from August 16, 2011.

The USO drifts observed by the reconstructive transponder are not within specifications for the HY-2A altimeter USOs. However, before HY-2A' s launch, no abnormal USO frequency changes were detected. The HY-2A altimeter research group and USO supplier have not yet determined the cause of the observed USO drift. Both side A and side B USO frequencies increase with age. HY-2A altimeter side A operated from August 2011 to March 2013, while side B remained in cold standby redundant status. Therefore, side A USO frequency reached 35 Hz and dropped, then side B USO was activated, and side B' s actual frequency began to increase. Side A USO voltage anomaly behaviors led to the decision to completely turn off side A, and the relationship between side A USO' s frequency drop on March 31, 2013 and the USO malfunction has yet to be verified. No other abnormal behavior of side B' s USO was observed except for large oscillator drift, and side B was determined fit for the HY-2A altimetry mission. HY-2A altimeter USO drift is larger than most long-term drifts of different DORIS onboard oscillators but smaller than Jason' s [?], so such a significant USO shift is not without precedent.

B. USO Drift Verification by Multi-Mission Cross-Calibration

USO drift in HY-2A altimeter IGDR products has not been corrected. According to [?], MSL bias of HY-2A altimeter containing USO drift can be expressed as:

$$\text{MSL Bias} = \hat{MSL}_{HY-2A} - \hat{MSL}_{ref} = \text{Bias}_{USO} + \text{Bias}_{others} \tag{11}$$

where MSL Bias is HY-2A altimeter MSL bias, $\hat{MSL}_{HY-2A}$ is HY-2A altimeter MSL, $\hat{MSL}_{ref}$ is reference radar altimetry mission MSL, Bias_{USO} is bias introduced by HY-2A altimeter USO drift, and Bias_{others} is residual bias. We assume Bias_{others} is constant, so the slope of Bias_{USO} equals the slope of MSL Bias.

MSL Bias is obtained from cross-calibration between reference radar altimetry missions and HY-2A. Cross-calibration uses a 300-second time window and 5-km spatial window. Jason-1 and OSTM/Jason-2 missions serve as reference missions. USO corrections from the reconstructive transponder are used to correct MSL Bias. Jason-1 GDR-C/D data and OSTM/Jason-2 GDR-D data from January 2012 to February 2014 provide reference MSLs.

Figure 5: see original paper shows the MSL Bias series using Jason-1' s MSL for cross-calibration with HY-2A altimeter' s MSL, and Figure 5: see original paper shows corrected MSL Bias using (11). The drift of corrected Jason-1-HY-2A MSL Bias is $1.55 \times 10^{-4} \pm 2.54 \times 10^{-4}$ m/day. The Jason-1 mission ended in July 2013, and Jason-1 GDR data corresponding to HY-2A altimeter side-B data are insufficient for analysis.

Figure 6: see original paper shows the MSL Bias series using Jason-2' s MSL for cross-calibration with HY-2A altimeter' s MSL, and Figure 6: see original paper shows corrected MSL Bias using (11). The drift of corrected Jason-2-HY-2A side A MSL Bias is $2.42 \times 10^{-4} \pm 2.92 \times 10^{-4}$ m/day, and the drift of side B MSL Bias is $2.04 \times 10^{-5} \pm 6.69 \times 10^{-5}$ m/day.

V. CONCLUSION

Though further long-term calibration campaigns using tide gauge networks are necessary to validate HY-2A altimeter USO drift, the reconstructive transponder provides USO correction that reduces the 40 cm/year drift of HY-2A altimeter MSL significantly to 88.3 ± 106.5 mm/year (side A-Jason-2 comparison) and to 7.4 ± 24.4 mm/year (side B-Jason-2 comparison). To date, the reconstructive transponder calibration site has not been fixed at a specific HY-2A crossover. Furthermore, several complete losses of responding signal occurred due to (1) uncertainty in orbit prediction for calculating the reconstructive transponder' s preset delay, and (2) the limited range window length of HY-2A altimeter in search mode. To reduce these losses, we suggest placing the reconstructive transponder at the satellite crossover to improve USO drift estimation accuracy. We also recommend prolonging the range window of future radar altimetry missions to obtain more altimeter observations during transponder calibration.

Estimating altimeter USO drift using the reconstructive transponder not only provides a novel approach for estimating and calibrating satellite radar altimeter USO drift but also introduces a method for understanding oscillator aging characteristics. Additionally, the onboard USO drift calibration approach for HY-2A follow-on radar altimetry missions has been improved.

APPENDIX: TROPOSPHERIC AND IONOSPHERIC DELAYS ANALYSIS

The 3 dB beamwidth of the zenith-pointing reconstructive transponder antenna is 1.8 degrees at Ku-band, and the HY-2A altimeter range window is 60 meters wide in search mode. The limited length of the HY-2A altimeter range window and the beamwidth of the reconstructive transponder antenna ensure that the angle between the boresight of the reconstructive transponder antenna and the line from the altimeter antenna phase center to the reconstructive transponder antenna phase center is no more than 1 degree when reconstructive transponder signals are in the altimeter range window. Tropospheric and ionospheric delays can be approximated as constants under small-angle conditions.

Total zenith tropospheric delay comprises a hydrostatic component d_{dry} and a wet component d_{wet}. The value of d_{dry} is about 2.3 m and relatively stable. The value of d_{wet} is small but changes rapidly with time. Tropospheric delay at zenith angle z can be written as:

$$D_{tro}(z) = m_d(z)d_{dry} + m_w(z)d_{wet} \tag{13}$$

where $m_d(z)$ and $m_w(z)$ are hydrostatic and wet mapping functions, respectively [?]. D_{tro} equals total zenith tropospheric delay when $z = 0^\circ$. Niell hydrostatic and wet mapping functions with the same expression:

$$m(z) = \frac{1}{\cos(z) + \frac{a}{1+b}} \tag{14}$$

and different a, b, c values in [TABLE:II] are used in (14) [?], [?].

Ionospheric delay $D_{ion}(z)$ can be written as:

$$D_{ion}(z) = d_{iz} \times \left[1 - \left(\frac{R_e \sin(z)}{R_e + h_1}\right)^2\right]^{-1/2} \tag{15}$$

where d_{iz}, R_e, and h_1 are zenith ionospheric delay, Earth' s radius, and height of the maximum electron density layer above Earth' s surface [?]. The first-order Taylor series expansion of (13) and (15) near $z = 0$ yields:

$$\begin{aligned} D_{tro} &\approx d_{dry} + d_{wet}; \quad |z| \approx 0 \\ D_{ion}(z) &\approx d_{iz}; \quad |z| \approx 0 \end{aligned} \tag{16}$$

a, b, c values in [TABLE:II] are adopted considering future alternative in situ calibration sites. Assuming $d_{dry} = 2.3$ m, $d_{wet} = 0.4$ m, $d_{iz} = 0.3$ m (corresponding to Ku-band frequency), $R_e = 6371$ km, and $h_1 = 350$ km, [Figure 7: see original paper] presents the approximation error when using (16) and (17).

The total error introduced by tropospheric and ionospheric delay approximations is no more than 1 mm at $|z| \leq 1^\circ$; therefore, the zenith path delay introduced by the troposphere and ionosphere can be taken as constants D_{tro} and D_{ion}.

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